Aging Effects Across the Metal-Insulator Transition in Two Dimensions

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Aging effects in the relaxations of conductivity of a two-dimensional electron system in Si have been studied as a function of carrier density. They reveal an abrupt change in the nature of the glassy phase at the metal-insulator transition (MIT): (a) while full aging is observed in the insulating regime, there are significant departures from full aging on the metallic side of the MIT, before the glassy phase disappears completely at a higher density n_g; (b) the amplitude of the relaxations peaks just below the MIT, and it is strongly suppressed in the insulating phase. Other aspects of aging, including large non-Gaussian noise and similarities to spin glasses, also have been discussed.

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The glassy freezing of electrons, resulting from the competition between disorder and strong electron-electron interactions, may be crucial for our understanding of the behavior of many materials near the metal-insulator transition (MIT) [1]. The dynamics of such electron or Coulomb glasses [2], however, remains poorly understood, and experimental studies [3, 4, 5] are still relatively scarce. In two dimensions (2D), moreover, even the very existence of the metal and the MIT have been questioned. Although there is now considerable experimental evidence in favor of such a transition [6], there is still no general agreement even on the fundamental driving force for the 2D MIT. Theoretical proposals describing the 2D MIT as the melting of a Coulomb glass [7, 8, 9] have found support in observations and studies of glassiness [10, 11, 12, 13] in a 2D electron system (2DES) in Si. Aging [14, 15], one of the key characteristics of glassy materials, also has been demonstrated in this system [13], but its properties have not been investigated in detail. Surprisingly, although consistent with theory [9], glassiness sets in on the metallic side of the MIT [10, 11, 12], *i.e.* at an electron density $n_g > n_c$ (n_c– the critical density for the MIT), thus giving rise to an intermediate, poorly metallic and glassy phase between the metal and the (glassy) insulator. Here we focus on aging effects, which have been instrumental as a probe of complex nonequilibrium dynamics in many types of materials. We find an abrupt change in the aging properties that occurs at n_c. The observed change in the dynamics at the 2D MIT itself, in addition to that at n_g [10, 11, 12], might help to determine the validity of different theoretical pictures.

The system is said to exhibit aging if its response to an external excitation depends on the system history in addition to the time t. In electron glasses, aging has been studied mostly and most easily [4] by looking at the relaxations of conductivity $\sigma(t)$ towards its equilibrium value σ_0 after a temporary change of electron density n_s during the waiting time t_w. Aging is observed if $t_w \ll \tau_{eq}$ (τ_{eq} – equilibration time), *i.e.* if the system is not able to reach equilibrium under the new conditions during t_w. It is manifested in the dependence of $\sigma(t)$ on t_w such that, in those strongly localized systems, the aging function $\sigma(t, t_w)$ is just a function of t/t_w [4]. This is known as simple, or full aging. It is interesting that, in spin glasses, full aging has been demonstrated only relatively recently [16]. In general, however, the existence of a characteristic time scale t_w does not necessarily imply simple t/t_w scaling [17]. In the mean-field models, in fact, two different cases are distinguished: one, where full aging is expected, and the other, where no t/t_w scaling is expected [18]. Experimentally, departures from full aging are common [14, 15]. In a 2DES in Si, where $\tau_{eq} \to \infty$ as temperature $T \to 0$ (hence glass transition $T_g = 0$) [12], aging was also observed for $t_w \ll \tau_{eq}(T)$ [13] using the experimental protocol described above. The goal of this study is to investigate that aging regime in detail. In particular, unlike previous work [13], here T is kept fixed at 1 K such that τ_{eq} is astronomical [19] and the 2DES is always deep in the $t_w \ll \tau_{eq}$ limit; $\sigma(t, t_w)$ are then explored systematically both as a function of final n_s and of the difference in densities during and after t_w. Our main results include: a) $\sigma(t)$ obey a power-law dependence for $t \lesssim t_w$ and a slower relaxation law for $t \gtrsim t_w$, thus showing a memory of the time ("age") t_w; b) $\sigma(t, t_w)$ exhibit full aging for $n_s < n_c$; c) as n_s increases above n_c, there is an increasingly strong departure from full aging that reaches maximum at $n_s \simeq n_g$; d) for a given t_w, the amplitude of $\sigma(t)/\sigma_0$ has a peak at $n_s \lesssim n_c$, reflecting an interesting and surprising *suppression* of the relaxations on the insulating side of the 2D MIT.

The experiment was performed in a ^{3}He system (base $T = 0.24$ K) on the same (100)-Si metal-oxide-semiconductor field-effect transistors that were used in previous studies [12, 13]. The two devices (A and B, with 1×90 μm^2 and 2×50 μm^2 length$\times$width, respectively) had a 50 nm oxide thickness, and a relatively large amount of disorder (the 4.2 K peak mobility ≈ 0.06 m^2/Vs with the substrate (back-gate) bias [20] $V_{sub} = -2$ V). n_s was varied by the gate voltage V_g, such that $n_s(10^{11}\text{cm}^{-2}) = 4.31(V_g[\text{V}] - 6.3)$; $n_g(10^{11}\text{cm}^{-2}) = (7.5 \pm 0.3)$ and $n_c(10^{11}\text{cm}^{-2}) = (4.5 \pm 0.4)$, where n_g

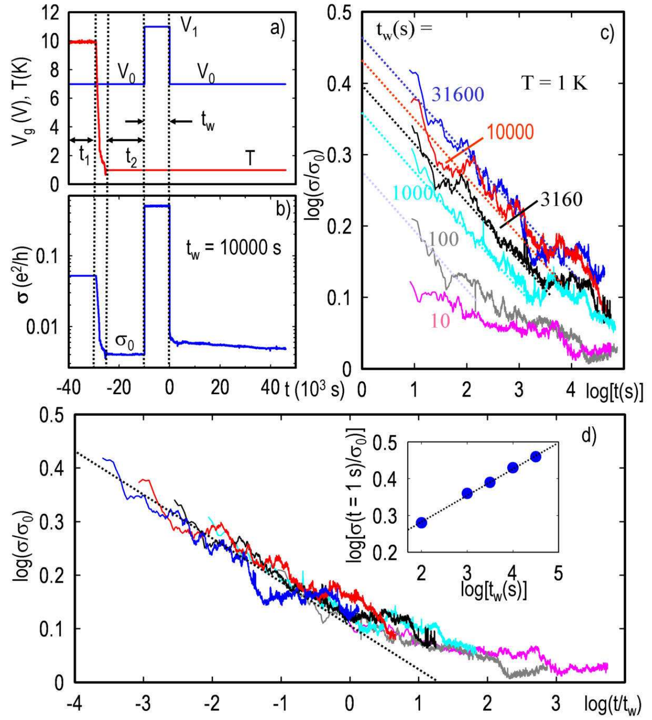

FIG. 1: (color online) (a) $V_g(t)$ and $T(t)$ in a typical experimental protocol, which always starts with the 2DES in equilibrium at 10 K [13]. The results do not depend on the cooling time (varied from 30 minutes to 10 hours), nor on t_1 and t_2 (varied from 5 minutes to 8 hours each). (b) The corresponding $\sigma(t)$. The relaxation of σ during t_w is too small to be seen on this scale. (c) $\sigma(t > 0)$ for several t_w, as shown; $V_0 = 7.0$ V [$n_0(10^{11}\mathrm{cm}^{-2}) = 3.02 < n_c$], $V_1 = 11$ V [$n_1(10^{11}\mathrm{cm}^{-2}) = 20.26$]. The data are not shown for the first few seconds (comparable to our sampling time ~ 1 s). The dotted lines are linear fits for $t \leq t_w$. (d) The same data as in (c) but plotted *vs.* t/t_w. The dotted line is a fit for $t \leq t_w$ with the slope $-\alpha = -0.081 \pm 0.005$. Inset: $\sigma(t = 1\mathrm{s})/\sigma_0$ *vs.* t_w. The dotted line is a fit with the slope $\alpha = 0.076 \pm 0.005$.

was determined from the onset of slow, correlated dynamics in noise and n_c from $\sigma(n_s, T)$ measurements on both metallic and insulating sides [10, 11]. The devices and the standard ac lock-in technique (typically 13 Hz; 5–10 μV excitation voltage) were described in more detail elsewhere [10]. The two samples exhibited an almost identical behavior. Unless noted otherwise, the data presented below were obtained on sample A.

We employ the so-called "gate protocol" [4], where V_g is changed from an initial value V_0 (density n_0), where the 2DES is in equilibrium, to another one, V_1 (density n_1), where the system attempts to equilibrate during t_w, but $t_w \ll \tau_{eq}$ [Figs. 1(a) and 1(b)]. After V_g is changed back to V_0 at $t = 0$, the relaxation of the "excess" conductivity $\sigma(V_0, t)/\sigma(V_0)$ is studied. Figure 1(c) shows some $\sigma(t)$ measured for several t_w and $n_0 < n_c$. Although $n_1 > n_g$, small amplitude relaxation during t_w is still visible [12, 13, 21]. It is clear that t_w has a significant effect on $\sigma(t)$.

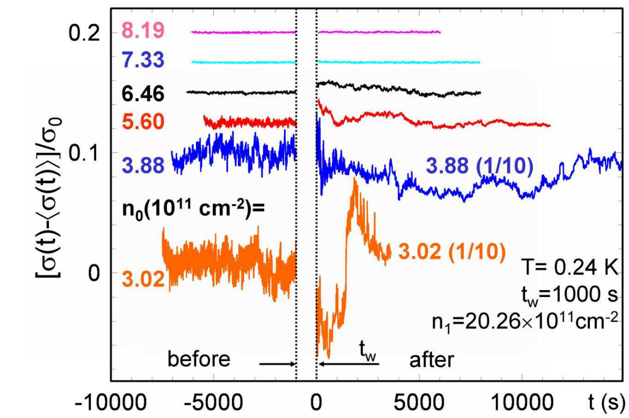

FIG. 2: (color online) Noise in σ for several n_0, before and after a change of n_s to n_1 during t_w. The slowly relaxing background $< \sigma(t) >$ has been subtracted from the upper 3 "after" curves. The data are shifted for clarity. For the two lowest n_0, the signals measured after t_w were divided by 10.

In fact, all the $\sigma(t, t_w)$ data can be collapsed onto a single curve simply by rescaling the time axis by t_w [Fig. 1(d)]. Therefore, in this case, the system exhibits full aging at least up to $t \approx (2–3)t_w$. We note that the relaxations can be described by a power law $\sigma(t)/\sigma_0 \propto (t/t_w)^{-\alpha}$ for times up to about t_w, followed by a slower relaxation at longer t. This means that the memory of t_w is imprinted on the form of each $\sigma(t)$. As a consistency check, the fits to the individual $\sigma(t)$ for $t \leq t_w$ [see Fig. 1(c)] yield the initial amplitudes of the relaxation $\sigma(t = 1\ \mathrm{s})/\sigma_0 \propto t_w^{\alpha}$ [22] with the same value of α (Fig. 1(d) inset).

The quality of the data collapse is difficult to estimate with high precision since $\sigma(t)$ are quite noisy. We argue that the large non-Gaussian noise seen in Fig. 1(c) is intrinsic to aging, similar to other materials out of equilibrium [17, 23]. Indeed, Fig. 2 shows that, for $n_s < n_g$, the noise after a temporary n_s change is much larger than the noise before the change. At the lowest n_0, this difference amounts to more than an order of magnitude. While a more detailed comparison of the "before" and "after" noise will be presented elsewhere, we note the following. First, the noise in the aging regime grows with decreasing T, while at the same time the relaxations $\sigma(t)/\sigma_0$ become smaller. Therefore, in order to optimize the signal to intrinsic sample noise for the study of aging, most of the data were taken at 1 K. Second, they show that the previous noise studies in a 2DES [10, 11] were actually performed in the aging regime, since V_g was varied at $T \sim 1$ K albeit in small steps ($\Delta V_g = 0.1$ and 0.01 V, or smaller, in Refs. [10] and [11], respectively). Such small ΔV_g did not produce any visible relaxations within the noise, consistent with the results below (Fig. 4).

Full t/t_w scaling is exhibited for all $n_s < n_c$. However, as soon as $n_s \gtrsim n_c$, we find systematic deviations from full aging [*e.g.* Figs. 3(a) and 3(c)]. In other glassy mate-

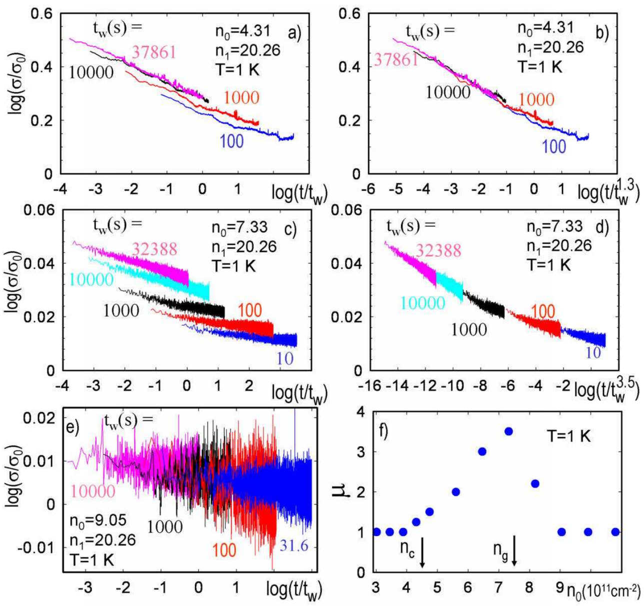

FIG. 3: (color online) (a), (c), (e) Relaxations for different $n_0(10^{11}\text{cm}^{-2})$ and a fixed $n_1(10^{11}\text{cm}^{-2})$, scaled with the waiting time t_w. (b), (d) Scaling with t_w^μ improves the collapse of the data. (f) μ *vs.* n_0. μ does not depend on n_1.

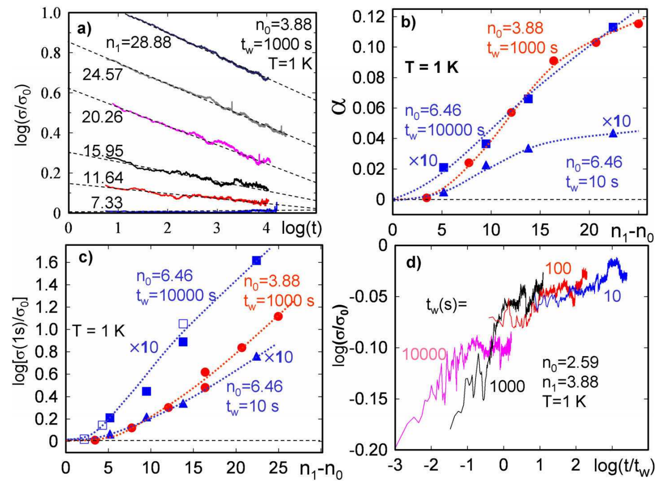

FIG. 4: (color online) (a) $\sigma(t)$ for fixed $n_0(10^{11}\text{cm}^{-2})$, t_w, and several $n_1(10^{11}\text{cm}^{-2})$. The dashed lines are fits. (b), (c) Slopes α and amplitudes $\sigma(t = 1\text{ s})/\sigma_0$ of the relaxations, respectively, *vs.* $\Delta n_s(10^{11}\text{cm}^{-2})$ for two fixed n_0 and several t_w. The values corresponding to $n_0(10^{11}\text{cm}^{-2}) = 6.46$ were multiplied by 10. Open symbols: device B. Dotted lines guide the eye. (d) Sample B. $\sigma(t)$ for small ΔV_g scaled with t_w.

rials [14, 24], it was found that the data could be scaled with a modified waiting time $(t_w)^\mu$, where μ is a fitting parameter ($\mu = 1$ for full aging). Even though μ may not have a clear physical meaning, the μ-scaling approach has proved to be useful for studying departures from full aging [14, 17]. By adopting a similar method, we find that it is possible to achieve an approximate collapse of the data [Figs. 3(b) and 3(d)]. The plot of μ *vs.* n_0 [Fig. 3(f)] shows a clear distinction between the full aging regime for $n_s < n_c$, and the aging regime where significant departures from full scaling are seen. It is striking that the largest departure occurs at $n_s \approx n_g$. For $n_s > n_g$, it appears as if the full aging is restored, but this may be an artifact of trying to collapse very small ($\sigma/\sigma_0 \lesssim 2$ percent) relaxations accompanied by instrumental (white) noise of comparable magnitude [Fig. 3(e)]. There are no relaxations, within the noise, for $V_0 \geq 9$ V at $T = 1$ K. We have also determined that μ does not depend on T.

Another important issue that needs to be addressed is the role of V_1 and of the step size $\Delta V_g = (V_1 - V_0)$. While μ depends only on V_0 (provided $t_w \ll \tau_{eq}$ at V_1), the amplitudes and the slopes of the relaxations for a given t_w do depend on ΔV_g. Figure 4(a) shows such an example, where $\sigma(t)$ are presented for fixed V_0, t_w, and different V_1. The data can be fitted by $\sigma(t)/\sigma_0 = [\sigma(t = 1\text{ s})/\sigma_0]\, t^{-\alpha}$ (t in units of s) at least up to $t \sim t_w$. The effect of ΔV_g on the slope α and the amplitude $\sigma(t = 1\text{ s})/\sigma_0$ is given in Figs. 4(b) and 4(c), respectively, for different V_0 and t_w. The increase of both quantities with ΔV_g is not too surprising, since larger ΔV_g lead to a higher number of new electrons in the 2DES during t_w, taking the system farther away from its original state at V_0. It is intriguing, though, that the results [Figs. 4(b) and 4(c)] seem to suggest that, for very small ΔV_g, both α and $\log[\sigma(1\text{ s})/\sigma_0]$ may become negative. This corresponds to $\sigma(t)$ approaching σ_0 from "below" instead of from above as in Fig. 1(c) [25]. Indeed, we have observed instances of such behavior, as shown in Fig. 4(d) for the case where both V_0 and V_1 happen to be in the insulating regime. The nonmonotonic dependence of the system response, here characterized by α and $\sigma(1\text{ s})/\sigma_0$, on the perturbation ΔV_g, bears a remarkable resemblance to the results of negative T cycle spin glass experiments (see Figs. 1–3 in Ref. [26]), where the so-called "memory anomaly" at low ΔT was interpreted [26] based on the hierarchical distribution of states in the free energy landscape. The noise studies in the aging regime [11] have already provided support for the hierarchical picture of glassiness in the 2DES. Unfortunately, it is not possible to perform systematic studies of aging for small, including negative, ΔV_g in a 2DES, because then $\sigma(1\text{ s})/\sigma_0$ is typically comparable to the large noise that is intrinsic to aging.

The raw data [*e.g.* Figs. 3(a), 3(c), and 3(e)], as well as Figs. 4(b) and 4(c), indicate also large variations in $\sigma(1\text{ s})/\sigma_0$ and α as a function of V_0 for fixed t_w and ΔV_g. This was explored in detail by varying V_0, while keeping t_w and V_1 fixed [Fig. 5(a)]. We expect, based on Fig. 4, to see an increase of both quantities with decreasing V_0, since ΔV_g is getting larger. While an increase is observed [Fig. 5(b)], it is much stronger than expected. For example, even for the same $\Delta n_s(10^{11}\text{cm}^{-2}) = 13.79$ and $t_w = 1000$ s, $\log[\sigma(n_0(10^{11}\text{cm}^{-2}) = 3.88,\ t = 1\text{ s})/\sigma_0] \approx 0.4$

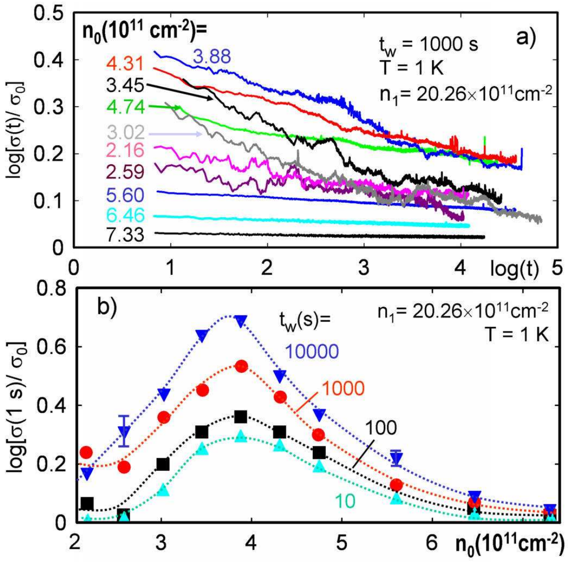

FIG. 5: (color online) (a) $\sigma(t)$ for fixed t_w, n_1, and several n_0. (b) Relaxation amplitudes *vs.* n_0 for several t_w. Dotted lines guide the eye. The error bars typical of low and high n_0 values are also shown.

[Fig. 4(c)], *i.e.* still an order of magnitude larger than for $n_0(10^{11}\mathrm{cm}^{-2}) = 6.46$. Even more striking, however, is the dramatic *decrease* of $\sigma(1\ \mathrm{s})/\sigma_0$ [Fig. 5(b)] as n_0 is reduced further, contrary to simple expectations based on Fig. 4. The slopes α exhibit the same nonmonotonic behavior [Fig. 5(a)]. Again, the abrupt change in the aging properties occurs at $n_s \approx n_c$: the relaxation amplitude peaks just before the system becomes metallic, and it is suppressed upon going deeper into the insulator. This is reminiscent of the suppression of the fluctuations of $\sigma(t)$ observed earlier in the same system at n_c (Ref. [10], Fig. 4 inset). While a clear understanding of these two effects is lacking, it is plausible that collective charge rearrangements that are responsible for the slow dynamics will be suppressed as the 2DES becomes strongly localized. It is interesting to speculate whether this is related in any way to the problem of many-body localization [27]. It would be also of interest to study aging deeper in the insulator, in the variable-range hopping regime, but that is not possible because of the small relaxation amplitudes and the large intrinsic sample noise. The effects of disorder could be explored further by extending the relaxation studies to cleaner 2DES, where $n_g \gtrsim n_c$ [11].

In summary, a detailed study of aging in a 2DES in Si shows an abrupt change in the nature of the glassy phase at the 2D MIT before it vanishes entirely at a higher density n_g. The results put constraints on the theories of glassy freezing and its role in the physics of the 2D MIT.

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